Preventing collisions involving surface mining equipment: a GPS-based approach

Todd M. Ruff [a,*], Thomas P. Holden [b]

[a] *Spokane Research Laboratory, National Institute for Occupational Safety and Health*

Abstract

Problem: An average of three workers a year are killed in surface mining operations when a piece of haulage equipment collides with another smaller vehicle or a worker on foot. Another three workers are killed each year when haulage equipment backs over the edge of a dump point or stockpile. Devices to monitor the blind areas of mining equipment are needed to provide a warning to operators when a vehicle, person, or change in terrain is near the equipment. *Method*: A proximity warning system (PWS) based on the global positioning system (GPS) and peer-to-peer communication has been developed to prevent collisions between mining equipment, small vehicles, and stationary structures. *Results*: A final system was demonstrated using one off-highway haul truck, three smaller vehicles, and various stationary structures at a surface mining operation. The system successfully displayed the location of nearby vehicles and stationary structures and provided visual and audible warnings to the equipment operator when they were within a preset distance. *Summary*: Many surface mining operations already use GPS technology on their mobile equipment for tracking and dispatch. Our tests have shown that it is feasible to add proximity warning to these existing systems as a safety feature. Larger scale and long-term tests are needed to prove the technology adequately. *Impact on Industry*: A PWSs that incorporates a combination of technologies could significantly reduce accidents that involve collisions or driving over an edge at surface mining operations.

Keywords: Proximity warning system; Collision; Global positioning system; Haulage equipment; Surface mining; Blind spots

1. Introduction

Each year, there are an average of 20 accidents and three fatalities involving collisions between a piece of surface mining haulage equipment and either a smaller vehicle or a worker on foot or some other object. Another 21 accidents occur and three mining equipment operators are killed each year when their equipment backs over the edge of an embankment, stockpile, or dump point (Fesak, Breland, & Spadaro, 1996; Mine Safety and Health Administration [MSHA], 2002). These accidents are caused by the operator's limited visibility from the cab of the equipment. In mining operations, these accidents most often involve large, off-highway dump trucks. The areas that an equipment operator cannot see while seated in the cab of these trucks can be extensive, depending on the size and type of equipment. Fig. 1 shows the blind areas around a 50-ton-capacity dump truck common in construction and sand and gravel operations. The gray shaded area outside of the truck outline shows those areas where the truck operator cannot see a 1.8-m-tall person. Larger trucks—up to 360-ton capacity—are common in mining, and the blind areas for these trucks can extend 12 m in front of the truck. Blind areas to the rear and right side can be even larger.

Researchers at the National Institute for Occupational Safety and Health (NIOSH) are investigating methods to reduce accidents attributed to the lack of visibility around mining equipment. Many technologies exist that can provide an operator with information on unseen objects or workers near the equipment, including video cameras, sensors, and mirrors. Many of these technologies have been popular in other industries, such as ultrasonic sensors in the automotive industry and video cameras on recreational vehicles, but very few have been successfully applied to mining equipment. Other technologies are being developed to address this problem and include electromagnetic signal

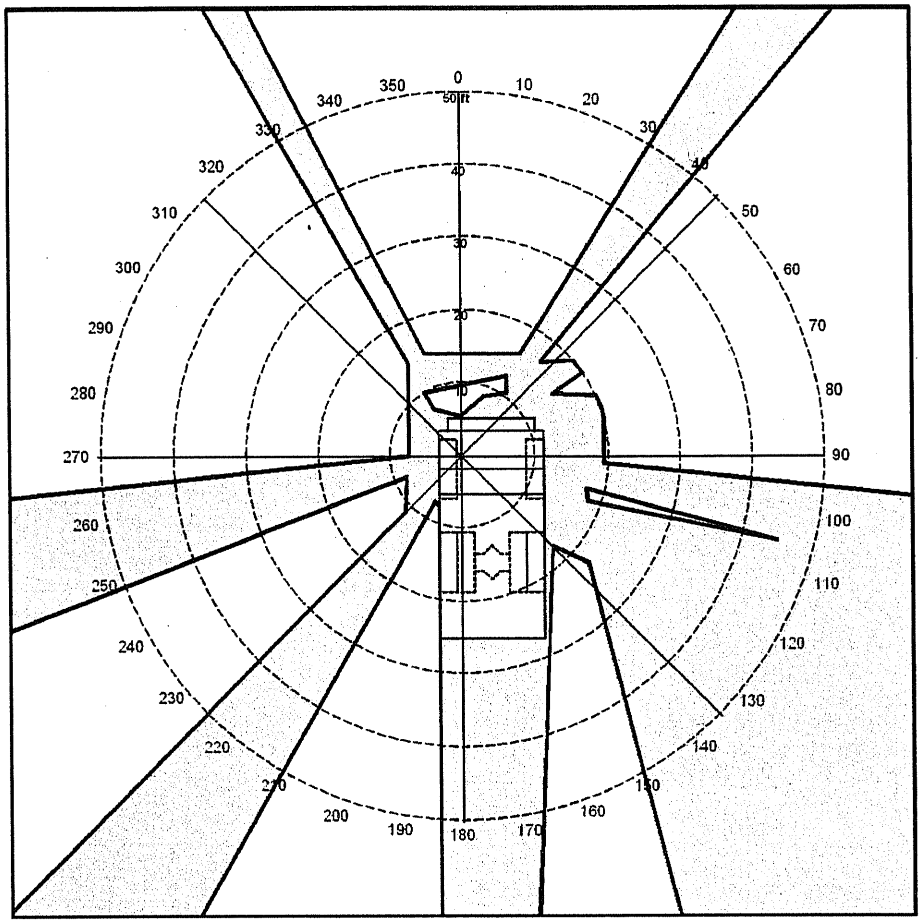

Fig. 1. Gray areas indicate where driver cannot see a 1.8-m-tall person from cab of a 50-ton-capacity dump truck.

detection and radar (Ruff, 2001). All of these technologies show promise for use on mining equipment; however, further development is needed to overcome the challenges associated with the harsh environment of mining and the size of the equipment being used.

Global positioning system (GPS) technology also shows promise for this application. Many surface mines already use GPS on equipment for tracking, dispatch, and control. A logical next step for this technology is to use it to track equipment, workers, and stationary structures and provide a warning when the possibility of a collision exists. The NIOSH Spokane Research Laboratory, Spokane, WA, in cooperation with Trimble,[1] Sunnyvale, CA, has developed a new system based on GPS technology that will provide an equipment operator with information on all other vehicles, stationary obstacles, and dump points near the machine.

2. System concept

The concept for GPS-based proximity warning for mining equipment entails the use of differential GPS receivers and radios on all equipment having reduced visibility, all smaller vehicles on the mine site, and all workers on foot. As illustrated in Fig. 2, the location of all moving objects must be determined and updated in real time, and this information must be transmitted to all nearby equipment

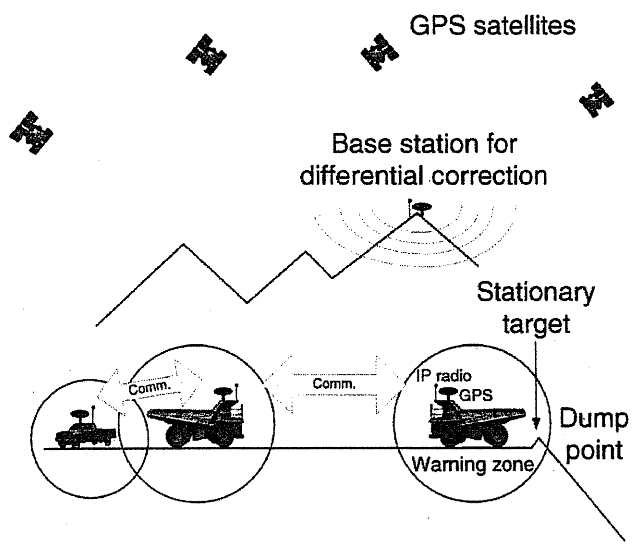

Fig. 2. The PWS concept.

[1] Mention of specific products or manufacturers does not imply endorsement by NIOSH.

so that the equipment operators are aware of other vehicles or workers nearby. In addition, the location of stationary structures, such as buildings, utility poles, and dump points, are stored in a database of potential obstacles. An alarm interface in the cab is required to provide a visual and audible warning when another vehicle, worker, or stationary obstacle is within a preset danger zone around the equipment.

The advantages of using GPS technology for proximity warnings at mining facilities include (a) the ability to use the existing GPS infrastructure at many mines, (b) the system's accurate location and tracking abilities, (c) low-to-zero occurrence of false alarms, (d) the capability of the system to identify obstacles, and (e) the ability to customize the user interface and warning zones.

Development of a GPS-based proximity warning system (PWS) by NIOSH and Trimble began in 2000. Prototypes were tested in an outdoor laboratory setting on passenger vehicles (Holden & Ruff, 2001). Development has progressed over the last 2 years, resulting in a mine-ready system that was demonstrated at the Phelps Dodge Morenci, copper mining operation in April of 2002.

3. Prototype system

3.1. System description

A prototype system was constructed to demonstrate that the idea of GPS-based proximity warning was feasible. Readily available components were used to keep costs at a minimum. Each system consisted of a laptop computer to: (a) collect, process, and transmit data, (b) run the PWS software, and (c) provide a display for the vehicle operator. A PCMCIA wireless network card (IEEE 802.11b) was used to communicate between laptops. An off-the-shelf, 12-channel, differential GPS receiver and antenna were used to determine location. A Coast Guard beacon was used to provide differential correction. Two complete systems were mounted in two different passenger cars for dynamic tests.

3.2. Test description and results

As described in Holden and Ruff (2001), the prototype system went through a series of operational and performance tests using two vehicles—a local vehicle and a remote roving vehicle. The goal of the operational tests was to verify the operation of the various pieces as compared to the defined specifications of the system. These specifications included the ability to set up, control, and monitor the GPS receiver properly, and the ability to send and receive information over a wireless local area network (LAN) connection.

One key factor was to determine the reliable transmission range of the wireless LAN. Maximum (11 Mbps) and minimum (1 Mbps) signaling rates were tested using the PWS software running on two laptops with wireless LAN cards installed. Each LAN card had a dual-patch diversity antenna directly mounted on it. The system functioned very well and had no packet losses when the two vehicles were separated by distances under 60 m. Beyond 60 m, performance declined. The ranges where transmission completely stopped were 120 m for the 11-Mbps signal and 220 m for the 1-Mbps signal. It was evident that the quality of signal reception was a function of range, antenna properties, and line-of-sight to the transceiver. Note that the wireless network antennas were connected to the PCMCIA cards, so antenna type and placement was limited. Signal reception can be made more reliable by using a better antenna mounted on the exterior of the vehicle.

Another important test of the wireless communications was the time-to-associate measure for a new vehicle entering a local area. At ranges of up to 60 m, the new vehicle associated, or was recognized by the PWS, in less than 1 s. Outside 60 m, the vehicle's time-to-associate was related to signal quality.

A second set of tests evaluated the performance of the system and covered the following items:

1. ability of the PWS to transfer information accurately, which was measured by matching received data from a remote vehicle and data from the local vehicle using GPS time tags,
2. latency of the remote vehicle information,
3. accuracy of the real-time vehicle position,
4. response to various dynamics of the remote vehicle, and
5. response to various dynamics of the local vehicle.

Provided that the communications link between the vehicles was functioning, the local vehicle's PWS was able to follow the trajectory of the remote vehicle according to the transmitted information. Errors were determined by matching real-time data stored by the remote system with the perceived remote data recorded by the local PWS using a GPS time mark corresponding to the transmitted information. Essentially, the information was matched in time so all latency errors were removed. These results showed that the errors introduced to the system by corrupt data transmissions were negligible, as no errors of significance were observed.

The latency of the information presented to an operator corresponds to errors in the actual position of the remote vehicle. Latency-induced error is dependent upon the velocity of the remote vehicle. Latency can be determined by special methods to roughly 0.2 s, assuming a broadcast rate of 4 Hz. In the tests, observed latency correlated well with this value. Additional sources of latency could be attributed to radio and processing delay. Overall, the system was measured to have a latency of less than 0.5 s.

Fig. 3 shows that radio coverage for these particular wireless network cards was excellent within a 100-m range. The position of the stationary local vehicle is near the

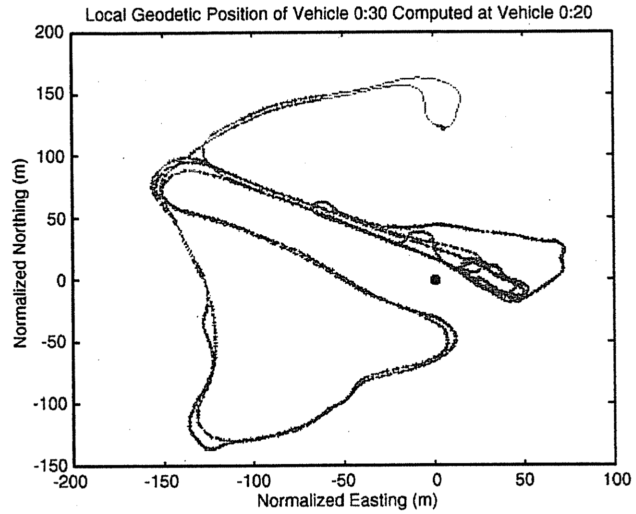

Fig. 3. Top view of remote vehicle's path as perceived by local stationary vehicle.

middle right of the figure (black dot). The thin line is the actual trajectory of the remote vehicle, and the dots are the perceived positions. Areas where the line is not covered resulted from communications interference from large obstacles. This demonstrates the line-of-sight nature of the short-range radios. Note that the communication gaps occurred over 100 m from the origin of the grid.

Fig. 4 shows the computed position errors of the moving remote vehicle as perceived by the stationary local vehicle. Errors of less than 2 m are evident. The graphs show that the errors were very small when the remote vehicle was stationary (flat line), but larger when it was in motion. The errors can be attributed to position update latency, but are within the desired specifications.

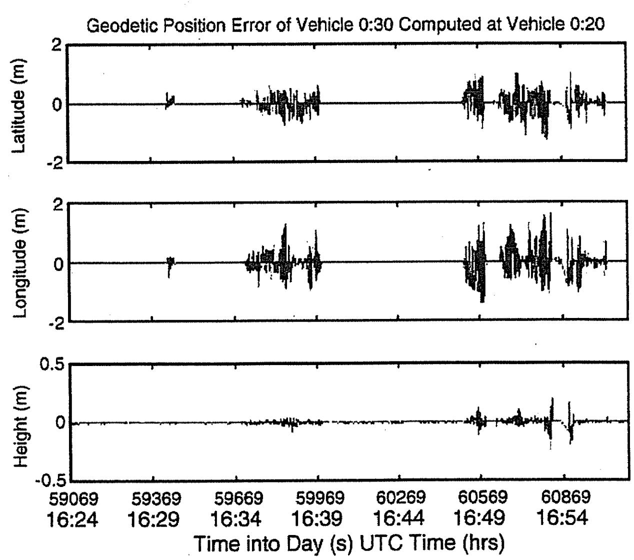

Fig. 4. Geodetic position error of moving vehicle computed at local vehicle.

4. Mine-ready system

4.1. System description

Tests of the prototype system showed that the concept of a GPS-based PWS was feasible; however, the system had to be redesigned using components that could be used on mining equipment. The mine-ready PWS consisted of the following Trimble components: (a) a GPS antenna, (b) a Windows CE-based computer with LCD display to run the PWS software, (c) an eight-channel, single-frequency, differential GPS receiver (integrated into the computer enclosure), and (d) a SiteNet 900-MHz Internet Protocol (IP) radio. All of these components were designed for mounting on heavy equipment.

The mine-ready PWS operates in a similar manner to the prototype system, but with a few modifications. As before, GPS is used to determine the location of the vehicle on which a system is mounted. Differential correction information from a base station is also received by the PWS. The corrected location of that vehicle is then transmitted once per second via the IP radio to all other vehicles in the area equipped with a PWS. The locations of other vehicles are also received by the IP radio and shown on the computer's display if they are within a specified range. The location of stationary obstacles, such as dump points, power lines, and mine buildings, does not have to be transmitted. Their coordinates can be entered into the system database so that they show up on the vehicle's display.

4.2. Test description and results

For tests at the Phelps Dodge Morenci Copper Mine, a complete PWS was installed on each of the following equipment: Caterpillar 797 360-ton capacity haul truck (Fig. 5), Caterpillar rubber-tire dozer (Fig. 5), and two service trucks (pickups). A base station was also installed

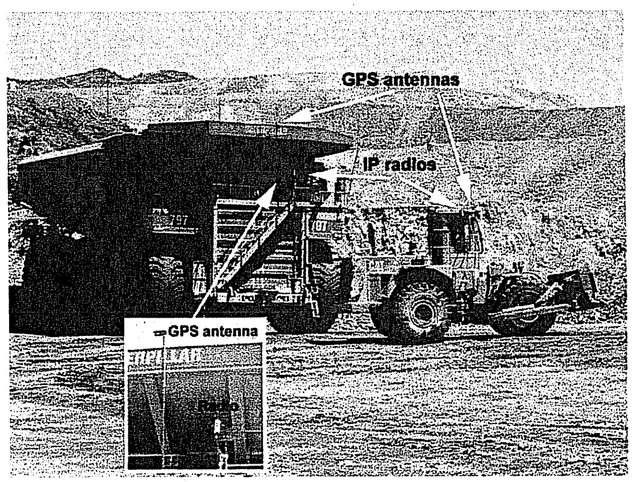

Fig. 5. PWS equipment installed on a Caterpillar haul truck and dozer.

on a nearby hill to provide differential correction information to the individual systems on the vehicles.

The GPS antennas and IP radios were temporarily, but securely, mounted on the mining equipment and service trucks in typical locations, usually on or near the cab roof. The computer was securely mounted in each vehicle in a fashion similar to a final, permanent installation. The PWS software ran on this computer and displayed a screen for the equipment operator that showed his/her equipment in the center, the detection zone radius, the warning zone radius, system status, and icons representing other vehicles or stationary obstacles in the area (Fig. 6).

Each vehicle's warning and detection zones were adjusted according to the vehicle's size. The display in Fig. 6 was mounted in the Caterpillar 797 haul truck and had a 30-m-radius warning zone and a 60-m-radius detection zone. The zones for the dozer and service trucks were set at 20 and 40 m. Audible alarms were generated whenever another vehicle or stationary obstacle was detected in either zone. In addition, the color of another vehicle's icon changed from green (outside both zones), to yellow (inside detection zone), to red (inside warning zone) as it approached the center of the screen.

The demonstration and tests were held in an active area of the Phelps Dodge Morenci Mine where production traffic was at a minimum. The test area consisted of a simulated loading area at the bottom of a small pit, a haul road, a dump area, and a large open area. A truck loading and dumping cycle, described below, was repeated several times to evaluate the reliability of the system.

1. Haul truck parked in staging area.
2. Haul truck drives down into pit, passing a simulated utility pole to show detection of a single stationary obstacle.
3. Service truck follows.

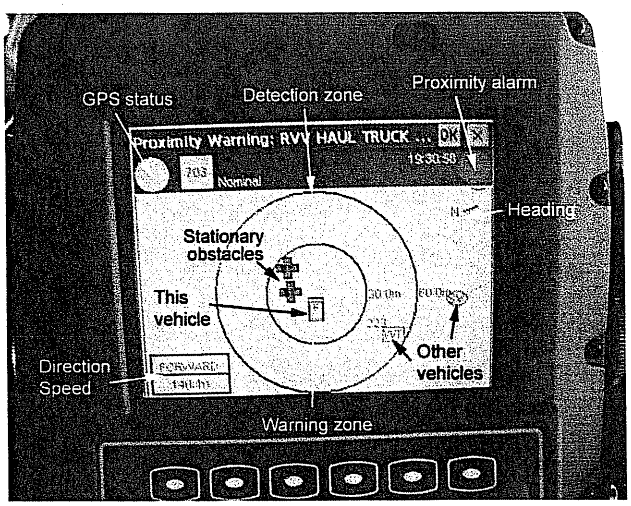

Fig. 6. PWS computer display.

4. Haul truck pulls into simulated loading area with the shovel represented by a set of three stationary obstacles.
5. Dozer works around pit area to show detection of a moving vehicle.
6. Service truck enters pit to show detection of multiple moving vehicles.
7. Haul truck leaves pit and drives up ramp to dump.
8. Service truck follows within 60 m to show tracking of two moving vehicles.
9. Haul truck backs into dump represented by two stationary obstacles to show detection of dump point.
10. Service truck pulls up and parks in haul truck's blind spot to show detection near the haul truck.
11. Repeat as necessary.

Another separate test was conducted to demonstrate the accuracy of the system. The dozer and haul truck were parked in the test area so that each was out of the detection zone. The dozer then slowly drove toward the haul truck and stopped when the haul truck's PWS indicated that the dozer reached the 30-m warning zone. The distance was then measured to check system accuracy. The distance between the GPS antennas, accounting for differences in antenna height, averaged around 28 m for this test.

Each system successfully tracked three other mobile vehicles and six stationary obstacles. Expected accuracy of the position of a vehicle or obstacle shown on the PWS display was 2–5 m using the computer's internal receiver with differential correction. Accuracy depends on many factors, including satellite positions (positional dilution of precision or PDOP), multipath interference, the status of Selective Availability (SA), and the type of GPS receiver used, to name a few. Observed accuracy was 2–3 m during the tests. Higher position accuracies could be obtained using higher quality, external GPS receivers, like those used with the prototype system.

One instance of multipath interference caused an error in vehicle location during preliminary tests. Multipath interference occurs when a satellite range signal reflects off objects and takes several paths before it reaches the receiver. This interference resulted in a service truck location that was briefly shifted by 15 m on the haul truck's screen. This was corrected as soon as the vehicle moved. However, methods to reduce multipath problems may need to be studied, including improved antenna designs and mounting locations. No other multipath errors were seen during the demonstration, and good location solutions were obtained even when a smaller vehicle was parked immediately next to the haul truck. This meant that the satellite constellation was adequate; the number of satellites visible to a vehicle never dropped below four, even when a larger vehicle blocked some of the satellites. This may change at different mine locations or at different times of the day because the constellation depends on these two factors.

No problems with satellite visibility were seen in the test area because of mine structures such as pit walls; however, in deep pits this may be an issue. Pseudolites (ground-based transmitters that simulate satellites) are being tested in another area of the Phelps Dodge Morenci Mine to supplement satellite coverage for GPS-assisted drilling equipment (Shields, Flinn, & Obregon, 2000). The use of pseudolites in any mine would increase the number of range transmissions used to calculate position, thereby increasing the accuracy and reliability of a PWS or any other system using GPS. The existing PWS would need to be modified to allow the use of pseudolites.

Some problems were seen that involved the other vehicle icons occasionally and briefly shifting position by a few meters on the haul truck's display while the truck was moving. Part of this was caused by the movement of the GPS antenna. The antenna on the haul truck was mounted on a long pole, which vibrated and whipped back and forth during abrupt truck movement. The sudden direction and velocity changes of the antenna sometimes confused the PWS, causing the position of the other vehicle icons to shift slightly. The shift was brief and could be remedied with a more rigid antenna mounting scheme or filtering algorithms. Slight errors in vehicle heading also contributed to the occasional position shifts seen during truck movement. Vehicle heading was calculated by comparing the current position solution with the previous one. Any error in position caused errors in the calculated heading. This could be remedied by integrating dead-reckoning methods and better algorithms for determining heading. These improvements will be made to future systems.

The system that was demonstrated did not have an input available for a reverse gear sensor or switch. In order for the display to always be aligned so that the top of the screen pointed forward, the system had to detect whether the truck was moving in forward or reverse. A temporary solution was implemented that required the driver to press a button when reverse gear was selected. This would be automatic in a final version of the PWS.

5. Discussion

In order for a mine-wide, GPS-based PWS to be effective, all vehicles, mining equipment, and workers on the mine property would need to be outfitted with a system. Functionality and cost of each system could vary with each type of vehicle. For instance, service trucks and contractor vehicles could be outfitted with a simple system that would not require the current computer/display. Such a system could use an off-the-shelf GPS antenna and receiver, a low-cost processor, and an IP radio all packaged in a single enclosure that attached quickly to the vehicle's roof. A simple audible warning would be generated in the cab of the vehicle when another vehicle or piece of equipment was nearby. The projected cost for this system would be around US$2,500 per vehicle.

The reduced visibility associated with larger mining equipment would require a more expensive and more functional system. A graphics display would be needed to allow the operator to locate and identify nearby obstacles. The PWS could stand alone like the mine-ready system described here, or it could be integrated into existing dispatch and control systems. The projected cost of a stand-alone system would be around US$10,000 for each piece of large mining equipment.

One obvious element missing from these tests was a system to protect a worker on foot. This would require a personal PWS that consisted of miniature GPS equipment, a small processor, and IP radio equipment. The system would need to fit on the belt or in the vest pocket of a worker. Hardware for a personal system is available, and software development is planned to begin next year at NIOSH.

If a GPS-based PWS were implemented now, some method of redundancy would be required to ensure that the equipment, smaller vehicles, and workers were protected 100% of the time, regardless of satellite visibility. Existing technology, such as cameras, radar, or a radio-frequency identification (RFID) tag system, also has limitations when used alone (Holden & Ruff, 2001). A combination of a GPS-based system and one of these other technologies could, however, provide the redundancy needed for a highly reliable system.

These preliminary tests at a surface mine showed that a GPS-based PWS has the potential to significantly reduce accidents that involve collisions or driving over an edge at surface mining operations. This is accomplished by providing operators with the location of objects, people, and vehicles that may be in the equipment blind areas. Future work will involve larger scale and longer term tests to prove this technology adequately. In addition, several improvements will be made to the proximity warning algorithms, such as the integration of dead reckoning methods and the ability to use pseudolite signals. The integration of additional sensor inputs for travel direction and other methods of monitoring blind spots will be needed to increase accuracy and reliability. The ability to protect workers on the ground will be the final element needed to complete this system.

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